

## **Internal Tides and Solitary Waves in the Northern South China Sea: A Nonhydrostatic Numerical Investigation**

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### **LONG-TERM GOALS**

The goal of this project is to understand processes relevant to the generation, propagation and dissipation of finite-amplitude internal solitary waves observed in the region from the Luzon Strait to the Chinese continental shelf.

### **OBJECTIVES**

With data available from field observations in Non-Linear Internal Wave Initiative (NLIWI), this project is to perform simulation of finite-amplitude internal solitary waves under scenarios in the northern South China Sea. The objective is to provide information on the characteristics of nonlinear internal waves for comparison with data collected from remote sensing, mooring measurements, and shipboard observations.

### **APPROACH**

Processes of wave generation, propagation and dissipation are studied by numerical simulation using a nonhydrostatic ocean model under different scenarios of bottom topography, stratification, and the amplitude of the tidal current. Experiments include wave generation by ridges in the Luzon Strait, wave propagation across the deep basin with an upper-ocean thermocline, wave reflection and diffraction near the Dongsha Island, wave generation and dissipation on the continental slope, and characteristics of higher-mode waves.

### **WORK COMPLETED**

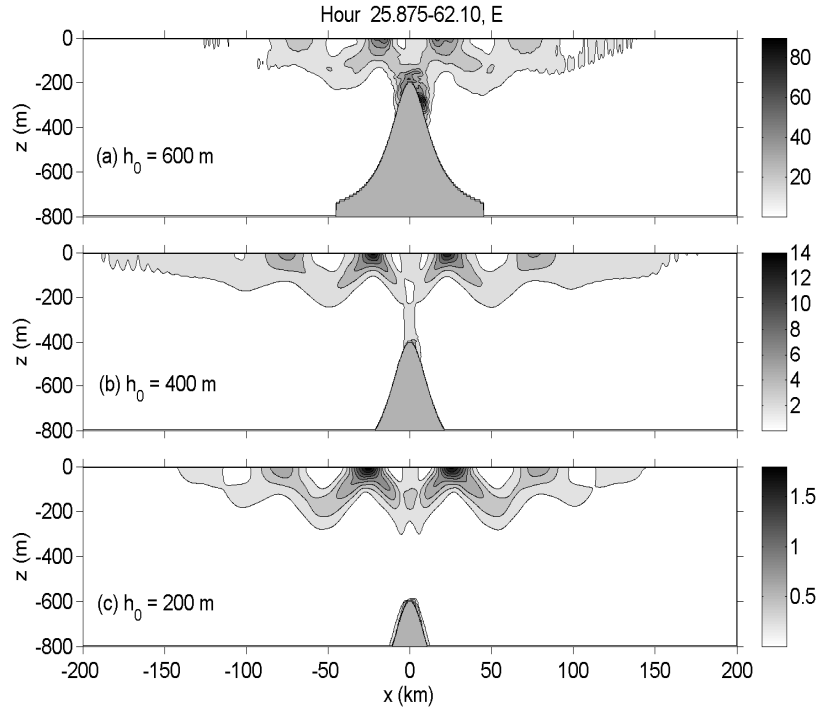
The process study of wave generation by Shaw et al. (2009) has been quantified in expanded parameter space. A relationship between the non-dimensional internal wave energy and the ratio of the topographic slope to wave slope has been derived and is supported by observed energy flux in the ocean. The result is presented in a Master of Science thesis (Qian, April 2010) and in a paper to appear in Deep-Sea Research I (Qian et al., 2010).

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## RESULTS

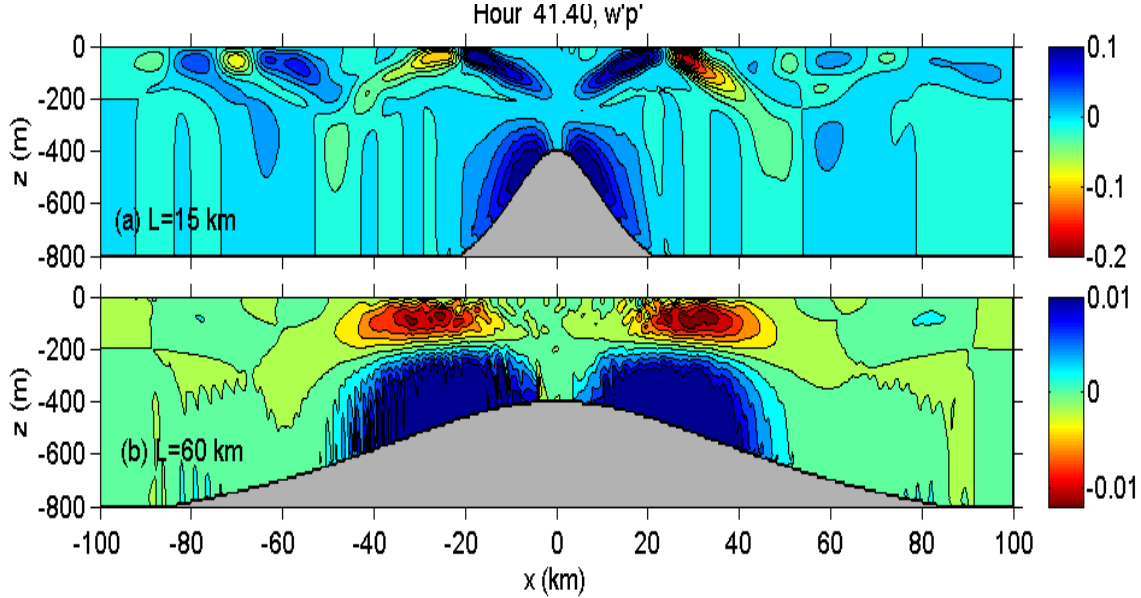
An important finding of Shaw et al. (2009) is the formation of wave beams over a supercritical ridge where the ridge slope is greater than the wave slope. By expanding the range of parameters, the present study has reached a comprehensive understanding of the effects of varying amplitude of the tidal current and stratification on the formation of wave beams and the energy conversion rate for ridges of different slopes and heights.

In the classical theory of internal wave generation, the averaged wave slope above the ridge determines whether the ridge is supercritical or subcritical. A surprise finding of this study is that the wave slope in the strongly stratified upper ocean, not the depth-averaged slope, affects the formation of wave beams. Figure 1 demonstrates the energy density of internal waves over three ridge heights,  $h_0 = 600$  m, 400 m and 200 m. The stratification at the ridge crest decreases rapidly from the 600-m ridge to the 200-m ridge. Nevertheless, the patterns of wave energy density in these three cases are similar qualitatively. Figure 1 suggests that the maximum wave slope in the upper ocean is appropriate for determining the slope parameter, the ratio of the topographic slope to the wave slope. The result is useful for determining whether a ridge is supercritical or subcritical,



**Figure 1. Distribution of internal wave energy density ( $\text{J/m}^3$ ) with ridge half width  $L = 15$  km for ridge heights  $h_0$  at (a) 600 m, (b) 400 m and (c) 200 m. The energy density is averaged over three tidal cycles from 25.88 to 62.1 hours. The contour intervals are 10, 2 and  $0.2 \text{ J/m}^3$  in panels (a), (b) and (c), respectively.**

The formation of wave beams has a strong effect on the energy flux emitting from the ridge. Figure 2 shows vertical energy fluxes over a narrow ridge and over a wide ridge. Wave beams form in the upper panel where the ridge is supercritical, and a modal structure appears over a subcritical ridge in the lower panel. With parameters other than ridge width being the same, the vertical energy flux is 10 times higher in Figure 2a than in Figure 2b. Large amounts of energy propagate away from a supercritical ridge to form internal solitary waves, while little energy escapes from a subcritical ridge.

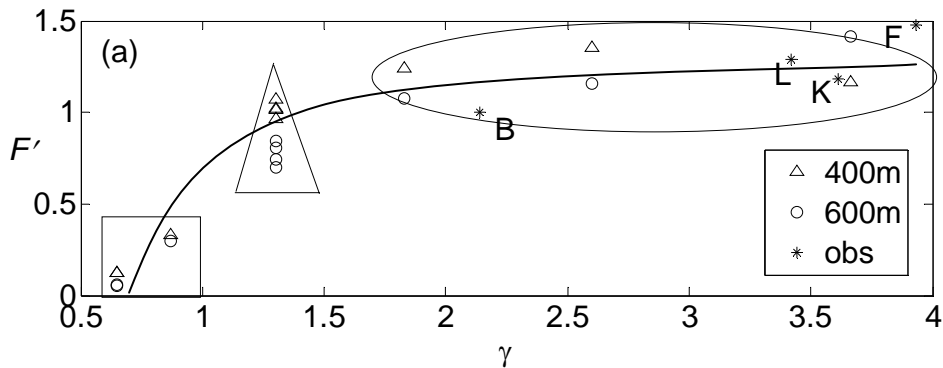


**Figure 2. Distribution of the vertical energy flux ( $W/m^2$ ) at 41.40 hours in experiments with ridge half widths (a) 15 km and (b) 60 km. The contour intervals are 0.02 and 0.002  $W/m^2$  in the two panels, respectively.**

In Figure 1, the maximum energy density is nearly proportional to the buoyancy frequency at the ridge crest, as expected in the linear internal wave theory. Experiments in this study further show that wave energy is proportional to the kinetic energy of the tidal current. These two scaling factors provide a scheme to normalize the energy flux of internal waves generated over a ridge. Normalized by the kinetic energy of the barotropic tides in the water column and the integral of the buoyancy frequency over the depth range of the ridge, the energy flux can be well represented as a function of the slope parameter in Figure 3. The symbol ( \*) represents estimates of the normalized energy flux in the ocean at Bay of Biscay (B), Luzon Strait (L), French Frigate (F) and Kauai Channel (K). The values from observations agree well with the relationship derived from the model study. Figure 3 indicates that the normalized energy flux is insensitive to the slope parameter and the height of the ridge for supercritical ridges.

The results have important implementations for internal waves in the ocean. First, a ridge may become supercritical at locations where the topographic slope is large and the upper-ocean stratification is strong. Large amounts of internal wave energy are converted from the barotropic tidal flow. In this case, the normalized energy flux is nearly constant and can be reliably estimated. Finally the scale factors for the normalization of the energy flux show that the energy flux is significant only when the amplitude of the barotropic tide is large (during spring tide) and when the ridge crest reaches the

strongly stratified upper ocean. This study suggests a way to estimate the energy flux of internal waves generated over steep, tall ridges.



**Figure 3.** Plot of the horizontal energy flux normalized by the kinetic energy of the barotropic tide and stratification at the ridge depth ( $F'$ ) as a function of the slope parameter ( $\gamma$ ) for ridge heights at 400 m (triangles) and 600m (circles). The symbol (  $*$  ) represents estimates in the ocean at Bay of Biscay (B), Luzon Strait (L), French Frigate (F) and Kauai Channel (K). The three regimes for small, near critical, and large  $\gamma$  are enclosed by a rectangle, triangle, and ellipse, respectively.

## IMPACT/APPLICATIONS

The results provide a practical method to calculate the energy flux of internal waves in the ocean.

## RELATED PROJECTS

The scheme derived from this study is being applied to estimation of energy flux in the Luzon Strait in two related projects (Award Numbers N00014-10-1-0319 and N00014-10-1-0470, PI: P. T. Shaw).

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Shaw, P.-T., D. Ko, and S.-Y. Chao (2009) Internal solitary waves induced by flow over a ridge: with applications to the northern South China Sea, J. Geophys. Res., 114, C02019, doi:10.1029/2008JC005007, 2009.

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